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DIGITAL AUDIO BROADCASTING:
Comparison of coverage at different frequencies and with different bandwidths

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Summary

A Digital Audio Broadcasting (DAB) system capable of reliable reception in vehicles and portables has been developed by the Eureka 147 project.

This Report describes a set of experiments performed to investigate the effect on the coverage area of changing the bandwidth of the DAB signal and its transmit frequency band.

It is concluded that the choice of a bandwidth for the DAB signal of approximately 1.5 MHz is suitable. This is because it is sufficiently wideband to provide a significant benefit in reducing the location variation of the total received signal power, whilst being narrow enough to allow suitable channelisation within the existing frequency bands.

It is also concluded that a frequency allocation below Band IV would be more suitable in order to provide satisfactory coverage for all types of reception from terrestrial DAB transmitters. Above this frequency, the effects of clutter and terrain undulations appear to increase significantly the problems of providing uniform coverage at low antenna heights.

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1. INTRODUCTION

FM sound broadcasting in Band II was designed as a high-quality system and can provide excellent sound quality. However, in recent years listeners' requirements of a radio system have changed. The advent of digital formats such as CD has created a demand for uniformly high audio quality from radio. People now expect high quality audio reception, including stereo, with increased reliability in vehicles and on portable radios. FM was designed to serve fixed installations with external antennas, and, though the introduction of mixed polarisation in the UK has gone a long way to assisting mobile and portable reception, FM does not cater fully for these new requirements.

In order to provide high-quality stereo reception to all receivers a Digital Audio Broadcasting (DAB™)* system capable of reliable reception in vehicles and portables has been developed by the Eureka 147 Project. The aim of DAB is to deliver near-CD quality stereo audio programmes in digital form to domestic receivers. In fact, the quality level can be controlled as a function of the digital capacity used, and hence number of channels carried, within the DAB multiplex. One of the limitations of conventional FM Radio is that the signal received by portable and mobile receivers is often degraded by multipath propagation. A DAB system should therefore be resistant to degradation in the presence of multipath. It should also be spectrally efficient. These factors give rise to a list of requirements which a new DAB system should fulfil:

- It should carry the programmes in digital form to prevent the successive small degradations that inevitably occur in an analogue broadcast system.
- It should be resistant to degradations in the presence of multipath propagation.
- It should provide efficient use of the RF spectrum.
- It should use a standard common to many countries to allow receivers to be produced at low cost.

This Report describes a set of experiments performed to investigate the effect on the coverage area of changing the bandwidth of the DAB signal and its transmit frequency band. It was conducted to support work being undertaken within the Eureka 147 Project to determine the optimum bandwidth for a DAB signal.

It was originally proposed that a 7 MHz bandwidth be used for DAB; however it became apparent that such a wide bandwidth would not be practical. Therefore it was necessary to investigate the effect of using lower bandwidths. It was expected that the effect of reducing the bandwidth would be to degrade the performance of the system. This is because the inherent 'frequency diversity' of the system would be reduced, so that it would be less able to cope with frequency-selective multipath effects.

2. DESCRIPTION OF THE CODING AND MODULATION SYSTEM

DAB is based upon a **C**oded **O**rthogonal **F**requency **D**ivision **M**ultiplex (COFDM) modulation system[1]. COFDM modulation uses a large number of RF carriers, each of which is QPSK modulated at a relatively slow symbol rate. The carriers are spaced in frequency such that, as each carrier is demodulated, there is no interference from data carried on adjacent carriers, i.e. they are orthogonally spaced. The digital audio signals are protected with convolutional coding and the resulting data is distributed across all the carriers in the RF band. Consecutive data samples are also separated in time. As a result, the audio data can still be recovered at the receiver, even if some of the carriers cannot be demodulated owing to anomalous propagation effects (such as multipath).

An additional feature has been added to improve the performance of the system in multipath environments. At the transmitter, each QPSK symbol is transmitted for longer than necessary to fulfil the requirements for orthogonal frequency spacing of the carriers. The extra time is known as the **guard interval**. At the receiver, an appropriate portion of this extended symbol (chosen to restore the orthogonal frequency relationship) is demodulated. The result is that echoes with a delay of less than the guard interval do not produce inter-symbol interference. The power in this multipath signal can then be used constructively to aid demodulation.

* DAB is a trademark claimed by one of the partners in the Eureka 147 project.

An extra advantage of this system is that simultaneous reception of the same information from more than one transmitter is possible. The delayed signals from the more distant transmitters will simply look like multipath. This can be used to provide more reliable coverage of an area. It also allows all the transmitters in a network to use the same frequency — thus providing excellent spectrum efficiency. This mode of operation is known as the Single Frequency Network (SFN).

DAB is being developed within the Eureka 147 Project which involves broadcasters, including the BBC, research institutes and manufacturers from many countries in Europe. A specification for the DAB system is being prepared by the members of the Eureka 147 Project and the EBU and is expected to be finalised soon as a European Telecommunications Standard. A shortened version forms part of the new CCIR (now ITU Radiocommunication Sector) Recommendations on digital sound broadcasting[2]. This should allow integrated circuits to be made which can be used throughout Europe, and possibly the world, with the benefits of economies of scale to produce receivers at an acceptably low cost.

3. NEW ASPECTS FOR PLANNING DAB SERVICES

There are a number of aspects that must be considered when planning DAB services which do not occur when planning conventional Radio and Television systems. These stem from three changes in the requirements, which are:

- DAB is planned to serve portable and mobile receivers. This assumes low receiving antenna heights, omnidirectional, low-gain antennas (rather than the 10 m high directional antennas assumed for Television and FM Radio planning), and ground clutter.
- DAB uses a digital modulation system. Whilst this has been designed to be very rugged, once onset of failure is reached, the received audio quality degrades very quickly with decreasing signal level. This contrasts with the relatively graceful degradation characteristics of Television and FM Radio signals.
- National and regional networks of DAB transmitters will be established as SFNs. This contrasts with conventional Television and FM Radio planning where separate frequency allocations must be found for each transmitter.

These differences have a number of implications for planning that must be considered, modelled and supported by experimental investigation.

3.1 Signal distributions

The desire to plan DAB services to portable and mobile receivers with low-gain, omnidirectional antennas and usually not line-of-sight paths to the transmitter, means that detailed consideration of the statistical distribution of the received DAB signal is required. Measurements of the variations in the received signal level that can be expected are required to quantify the effect of the frequency and time diversity which is inherent in the modulation system.

3.2 Location and time variations

The use of a digital modulation system which has a rapid failure characteristic means that greater accuracy in the planning of service areas is required.

When combined with the requirement to serve mobile and portable receivers, greater attention must be paid to considering the variations in signal level which occur in small areas and with time (as a result of changes in propagation conditions).

Field strength predictions and measurements are normally made for 50% (median) location values. Conventionally, if the median field strength in a particular area is equal to the minimum value for an acceptable service, the area is deemed to be served (assuming no interference or other effects need to be considered). In the case of an analogue system, there will still be a service to considerably more than 50% of locations, but with reduced quality. For a digital service such as DAB, however, this would not be the case. The transition from perfect quality to audio muting will occur over relatively few dBs, depending on the system characteristics. In view of the rapid degradation in digital systems, it is necessary to provide an adequate field strength in a high percentage of locations. A figure of 99% has been suggested for mobile reception. To achieve this, the median field strength must be increased by a suitable **location correction factor** (50 - 99% correction factor in this case).

The correction factor is an important factor in planning a DAB service. In general, a small value is desirable since it implies a lower median field strength requirement, and thus lower transmitter power. Since DAB is a much wider bandwidth signal than FM, there is a degree of frequency diversity. This has the effect of reducing the variations in the field strength

due to terrain effects, multipath, etc. Consequently, the location correction factor for DAB should be somewhat less than the value assumed for FM (19 dB for 50 - 99% correction)[3].

3.3 Spatial diversity

If an area is simultaneously served by several transmitters in an SFN, there is also a degree of spatial diversity, resulting in a further reduction in signal variation. This is another major advantage of the SFN principle, in addition to the benefit of the increase in the median field strength.

4. FACTORS AFFECTING THE COVERAGE OF DAB SIGNALS

When considering the performance of COFDM, and hence the coverage that can be obtained with a given transmitter, it is important to remember that there are a number of factors that can (to some extent) be traded-off against each other. These factors fall into four broad categories:

- Transmitter related factors,
- COFDM system related factors,
- Signal propagation factors.
- Receiver related factors.

Transmitter related factors include the conventional considerations of transmitter power, transmitter location, antenna gain, antenna height above ground level, antenna directivity, etc.

COFDM system factors affect the amount of time, frequency and spatial diversity that is available by choosing the time interleaving strategy, the occupied bandwidth of the signal and the guard interval respectively. A large enough guard interval allows signals from more than one transmitter to be received and successfully demodulated, and so provides transmitter spatial diversity.

Signal propagation factors include the effects of the terrain type, the transmit frequency used and local clutter on the field strength that is received.

Receiver related factors include the gain of the antenna that is used, the noise figure of the receiver, the shielding of the system to man-made noise (and other EMC considerations), and the vehicle velocity.

In any meaningful experiment, it is important to hold most of these factors within certain bounds whilst allowing one to vary in a controlled way. In addition, the constant factors must be fixed at representative values so that the significance of a variation elsewhere can be seen.

5. MEASUREMENTS REQUIRED

A number of areas were identified where experimental results were required to assist in the development of the DAB coding and modulation system and to provide information to improve the accuracy of planning techniques. Initially, these measurements focused on the area coverage as the bandwidth and transmitted frequency of the signal was varied.

Experiments were performed to investigate the effect of changing the COFDM bandwidth and transmit frequency on the coverage area of a DAB signal. The COFDM bandwidth was varied between 7 MHz and 1.75 MHz. Tests were conducted using Band IV and Band III transmit frequencies (531 and 211 MHz respectively). In one particular case, the effect of doubling the interleaving period was also investigated.

In the work described it was assumed that the local area field strength follows a log-normal distribution. Using this assumption, the 50 - 99% location factor is 2.33 times the standard deviation of the field strength. Thus, the location variation is generally expressed in terms of standard deviation.

Once the bandwidth of the Eureka DAB signal had been fixed at 1.5 MHz, measurements made at approximately that bandwidth were re-analysed to quantify the amount of location variation in different terrain areas, etc.

6. EXPERIMENTAL ARRANGEMENT

6.1 Transmitting equipment

The experimental signal was radiated from Crystal Palace which is the main London TV transmitter site, Fig. 1 *(overleaf)*. The signals were radiated from two independent antenna systems mounted at approximately 121 m above ground level. The 211 MHz antenna consisted of a vertical stack of two vertically polarised Yagi antennas, each with a gain of 7.5 dBd. The 531 MHz antenna consisted of a vertical stack of two vertically polarised log-periodic antennas, each with a gain of approximately 8 dBd. Both antenna systems had a 3 dB beamwidth of approximately 35°; with the main beam of the

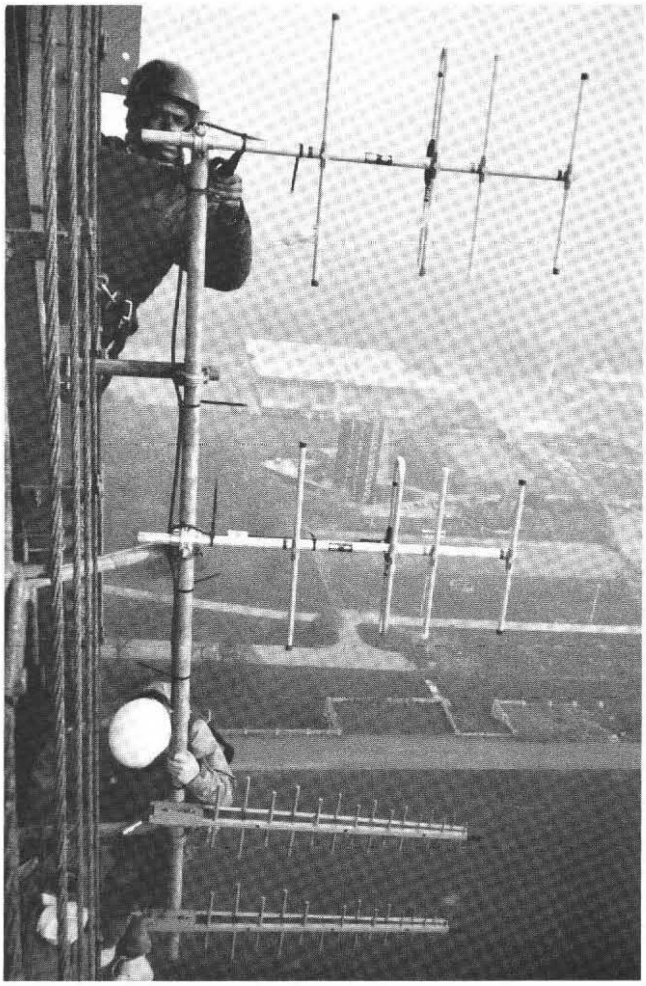


Fig. 1 - The antenna installation on the Crystal Palace transmitter.

antennas pointing due south, this system radiated power in a triangular area bounded by Crystal Palace, Addington and Sutton, Map 1 *(all maps are at the end of the Report).*

COFDM signals were generated by equipment which was placed in the transmitter hall at Crystal Palace. The digital signal used for the survey was a locally generated pseudo-random binary sequence (PRBS). A block diagram of the transmitting equipment is shown in Fig. 2. The Band III and Band IV signals were combined and fed to the power amplifier via a single feeder which had been installed for this work on the Crystal Palace tower. The power amplifiers were mounted on the tower in waterproof boxes close to the antennas.

The linearity of the equipment at each frequency was noted in the laboratory by measuring the intermodulation products (IPs) produced by two, equal amplitude, CW carriers at various output powers. After installation, the radiated ERP was then set by measuring the IPs produced by the equipment, and setting the power level of the carriers (at the bottom of the feeder) to produce IPs at the desired level. The CW carriers could then be replaced by the COFDM signal at the same power.

The COFDM equipment available allowed the bandwidth to be set at 7 MHz, 3.5 MHz and 1.75 MHz. In the first case, the change was achieved by halving the number of carriers transmitted. In the second case, the number of carriers was maintained but the symbol period was doubled (thus halving the carrier spacing). The area in which these experiments were conducted does not suffer from very long delay multipath, so the effect of changing the carrier spacing and guard interval was not significant.

Discussions with the COFDM equipment designers revealed that the number of 24 ms frames that the data is interleaved over could be reduced from 16 to 8. This meant that two experiments were possible; firstly, the effect of reducing the COFDM bandwidth and secondly, the effect of doubling the time interleaving period.

6.2 Receiving equipment

The receiving equipment was installed in a survey vehicle, Fig. 3.

The DAB receiver consisted of three parts; RF filters and amplifiers, the COFDM receiver and high-stability oscillator, and the measuring equipment. A block diagram of the equipment used is shown in Fig. 4 *(page 6)*. The RF filters and amplifiers were mounted in a waterproof box which was attached to the ground plane, underneath one of the monopoles.

Measurements were made of the horizontal radiation pattern of the quarter-wave monopole antenna at Bands III and IV. Since the initial survey work in South London was conducted with both antennas fitted at all times, the radiation patterns were measured with both antennas in place. The results are shown in Fig. 5. The gain variation is around ± 3.5 dB for Band III and ± 3 dB for Band IV.

240 V, 50 Hz mains power was supplied from a petrol-powered generator. This was mounted on the rear bumper of the measuring vehicle. To protect the equipment from loss of power and mains-borne interference, an uninterruptable power supply (UPS) was used to condition the supply and provide approximately 10 minutes support in the event of loss of power from the generator. The UPS was mounted in the back of the vehicle, beside the COFDM receiver and oscillator.

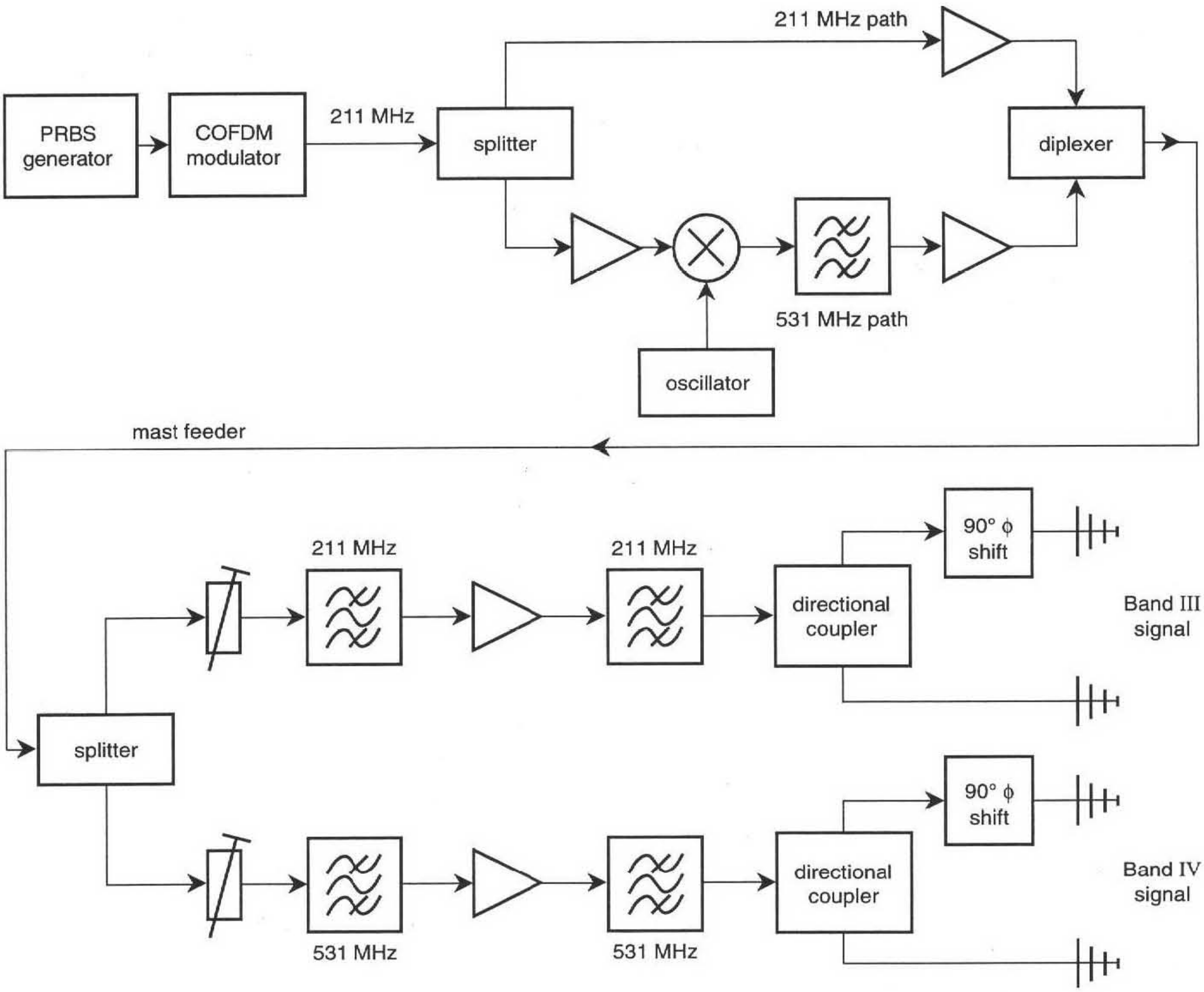


Fig. 2 - Block diagram of the transmitting equipment.

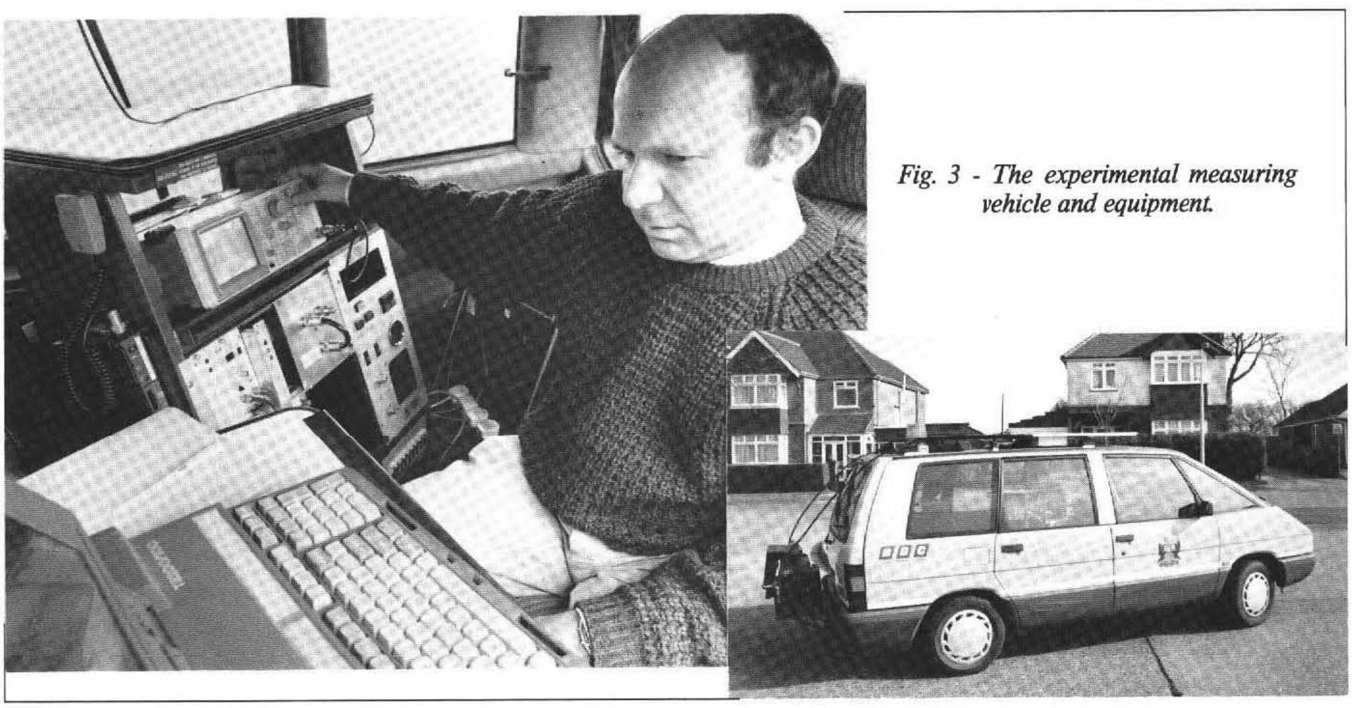


Fig. 3 - The experimental measuring vehicle and equipment.

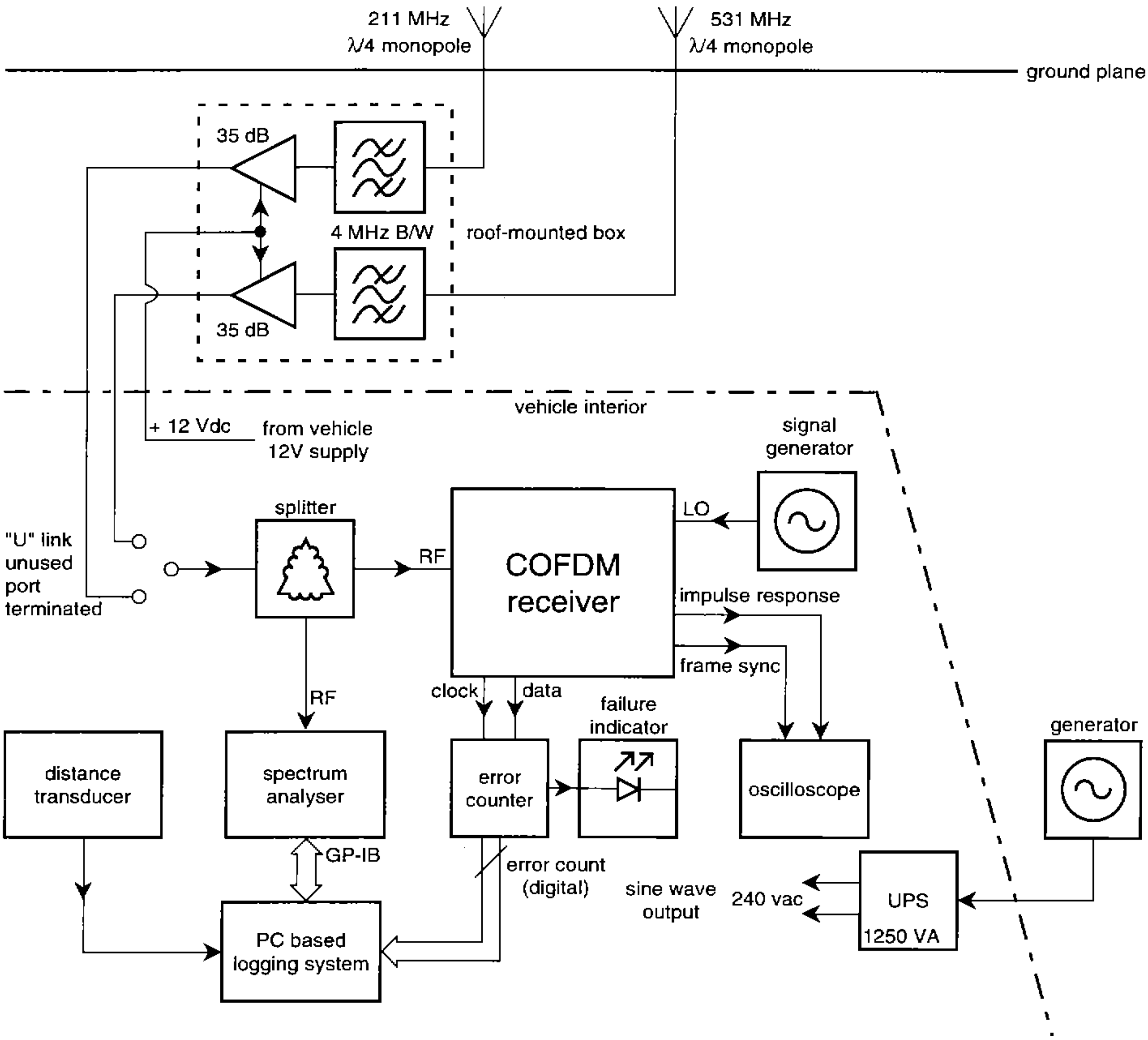
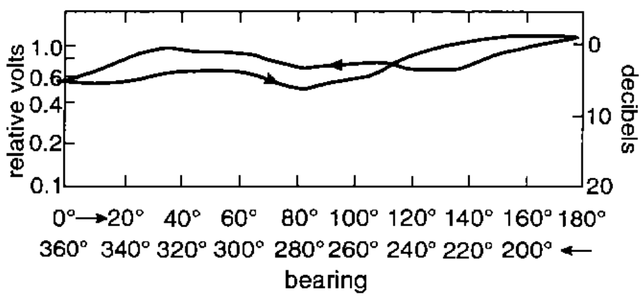
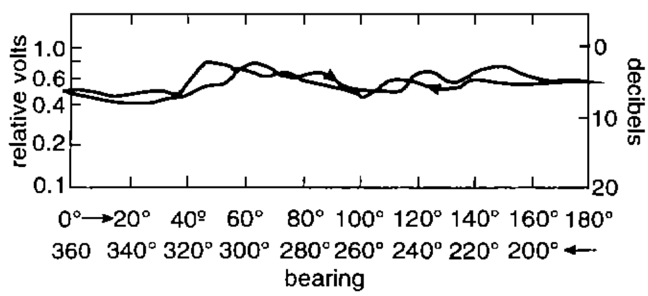


Fig. 4 - Block diagram of the receiving equipment.



(a) Horizontal radiation pattern of 211 MHz antenna with 531 MHz antenna in place.



(b) Horizontal radiation pattern of 531 MHz antenna with 211 MHz antenna in place.

Fig. 5 - Radiation patterns of the receiving antennas.

During the tests, the transmitter PRBS was received in the vehicle and demodulated. The error rate of received data was measured using a bit error rate (BER) counter connected to the COFDM receiver. A failure indicator was added to provide easy monitoring of when the BER lay in one of three states. These states were as follows:

- A *good signal*, where the BER was better than 1×10^{-5}.
- An *errored but decodable signal*, where the BER was worse than 1×10^{-5} but better than 1×10^{-1}.
- An *unusable signal*, where the BER was worse than 1×10^{-1}.

An oscilloscope and a spectrum analyser were incorporated in the measuring equipment. The oscilloscope was used to display the impulse response of the channel, which could be obtained from the COFDM receiver. The spectrum analyser was used to display the received RF spectrum. Both of these pieces of information were useful for understanding the cause of failure of the COFDM signal.

For some of the experiments, a computer-based logging system was used to record field strength values. This records field strength readings from the spectrum analyser via its GPIB interface. It should be noted that the measurements were actually of total received power, but they were converted to equivalent field strengths for ease of comparison with conventional service planning measurements and predictions. The system was also connected to a distance transducer which enabled it to take readings at regular intervals along the road. All readings were labelled with the map grid square in which they were taken. This required the operator to log when a grid boundary was crossed.

7. COVERAGE EXPERIMENTS

7.1 Experimental procedure

Suitable ERPs were radiated for each combination of frequencies and COFDM bandwidths. The differences were carefully chosen to allow the required effects in the change of coverage area to be seen. As the bandwidth of the COFDM signal was reduced, the ERP was reduced pro rata. This maintained the power-per-notional audio channel at a constant level. The effect of the reduction in COFDM bandwidth, and hence frequency diversity, could then be observed from the results.

Initially, the Band IV signal was radiated at an ERP 2 dB higher than the Band III signal. This difference was set to ensure that the received C/N, at an arbitrary distance from the transmitter, was the same at both frequencies — in the absence of differential propagation effects. Another way of looking at this is that the antenna couplings are different at the two frequencies, so that, with antennas of the same gain in an electromagnetic field of similar field strength, a different power would be received at the two frequencies. The difference for these frequencies is 8 dB (more power being received at the lower frequency). In addition, the levels of man-made noise are different at the two frequencies. This difference was measured at a few urban sites to be around 6 dB (more man-made noise at the lower frequency). The value seems reasonable, as Ref. 4 indicates that a value of 4 dB might be expected, but Ref. 5 suggests a value of 8 dB to be expected. The levels will vary greatly from location to location and so the measured value can only be taken as a rough indication of the relative levels.

In later experiments, the ERP of the Band IV signal was reduced to that of the Band III signal.

The following effective ERPs were used initially:

Band IV,	7 MHz bandwidth	140 W
Band IV,	3.5 MHz bandwidth	110 W
Band IV,	3.5 MHz bandwidth	70 W
Band III,	3.5 MHz bandwidth	70 W
Band III,	1.75 MHz bandwidth	35 W

The area to be surveyed was divided up into many small circular routes. The vehicle was driven around each of the routes twice, the first time monitoring one experimental condition and the second time monitoring another. The two laps were normally driven consecutively before moving on to the next area. This meant that the traffic conditions, weather, and other propagation factors were as similar as possible for the two measurements. Also, the vehicle was driven in the same direction both times in order to eliminate any directional characteristics in the receiving antennas, or reception differences between the two sides of the road. In all cases, the vehicle was driven as close as practicable to a speed of 40 km/h.

For later experiments, the same area was covered. As there was a delay whilst the transmitter ERP was adjusted, there were some variations in the traffic conditions, weather, etc. However, it is thought that the effect of these variations on the results was small, as there was good agreement when results were rechecked.

As the vehicle was driven around the chosen route, the reception quality was recorded on a map using coloured pens, one colour for each of the BER ranges discussed above. In this way, maps were prepared for each of the experimental conditions.

Whilst every care was taken to ensure that the experimental conditions were as similar as possible in each case, there will inevitably be variations. Therefore, all the results should be compared to determine the overall trends rather than pay close attention to minor differences.

7.2 Coverage results

Ref. 6 considers the experimental work that was performed using the 7 MHz COFDM bandwidth in some detail. These tests were conducted by measuring the received audio signal quality rather than the BER used in the later tests. The results, Map 2, shows areas where the received audio signal was either unimpaired or unintelligible. Due to the abrupt failure of digital systems, when they do fail, there are only a few areas where the audio quality was marginal or intermittently impaired. Such areas were marked by alternate stripes of the two conditions.

The results from the different experimental conditions are indexed in Table 1. The measurements were made using the BER of the received signal and are shown in the three ranges of BER given in Section 6.2. These correspond approximately to the categories obtained in the earlier experiment which monitored a received audio signal.

7.3 Comparison of results

To see the changes in coverage resulting from reducing the COFDM bandwidth from 7 MHz to 3.5 MHz, Maps 2 and 3 should be compared. In this case the comparison is inexact as it involves a mixture of subjective and objective measurements. However, the categories have been chosen so that the comparison is still meaningful.

To compare the changes in propagation at Band IV and III, Maps 4 and 5 should be compared.

To see the changes in coverage obtained with the same ERP radiated at Bands IV and III, Maps 3 and 4 should be compared.

To compare these results, consider three areas of the map. The first area lies near Selsdon and Addington and is the main road which can be found between map references ***l*7** and ***o*5**. This road lies on the south side of a hill and is not line-of-sight to the transmitting antenna on the Crystal Palace tower at either frequency.

The effect in this first area, of reducing the bandwidth of the COFDM from 7 MHz to 3.5 MHz, was to make the road totally unserved; whereas before, it was only largely unserved. On reducing the frequency from Band IV to Band III, the coverage of the road was improved. At the north end, where the road was closer to the crest of the hill, the result showed a significant improvement, in that much of the road became served — although in most cases the service was marginal. At the south end of the road, the changes were smaller.

The second area, is the road immediately to the west of Queen Mary's Hospital, and can be found between map reference ***d*7** and ***d*8**. This road lies in a shallow depression and is not line-of-sight to the transmitting antennas at either frequency.

The effect in this second area of reducing the bandwidth of the COFDM signal, was to render most of this area unserved. Previously, the road had been poorly served. The effect of reducing the frequency was to cause the road to become well served. In many places the received data still contained errors but the decoded audio would have been intelligible throughout.

The third area, is central Croydon. This can be found between map references ***i*4** and ***i*5**. According to the terrain database on which computer predictions

Table 1
Cross-indexing the test conditions with the figures showing the results.

Frequency Band	COFDM bandwidth (MHz)	ERP (W)	Interleaving period (ms)	Figure number
IV	7.0	140	384	7
IV	3.5	70	384	8
III	3.5	70	384	9
IV	3.5	110	384	10
III	1.75	35	384	11
III	1.75	35	768	12

are based, this area is line-of-sight to the transmitter at Crystal Palace. However, in practice, the area has a large amount of local clutter (i.e. tall buildings), which means that the received signal frequently suffers from severe multipath and diffraction of the direct signal.

The effect of reducing the bandwidth of the COFDM signal was to render areas of central Croydon unserved. In addition, over large amounts of the area, the received data contains errors, and hence these places become marginally served. A specific example is that reception in an underpass (marked on Map 1) was satisfactory at the wider bandwidth, but the system failed at the narrower bandwidth. The effect of reducing the transmitted frequency of the signal was to improve the reception in central Croydon dramatically. A few places remained marginal or unserved but in general the improvement was very significant. Reception in the underpass on the A212 was improved.

Comparison of Maps 3 and 5 shows that the effect of increasing the ERP by 2 dB was small. In fact, detailed comparisons show some cases where the system appeared to work better with a 70 W ERP than a 110 W ERP. Such anomalous results are due to variations in the experimental conditions (e.g. different amounts of traffic, different weather conditions, variations in vehicle speed, etc.). The main conclusion to draw from comparison of these figures is that the field strength variations over an area are large. More detailed statistics of the field strength variations are provided in Section 8; however, this result indicates that a large increase in ERP would be required to produce a significant improvement in the percentage of road length covered.

Map 6 shows the results of the survey with the COFDM signal occupying a 1.75 MHz bandwidth and the interleaving strategy adjusted to maintain the overall interleaving period. Map 7 shows the results of the survey obtained with the COFDM signal occupying a 1.75 MHz bandwidth and the interleaving strategy adjusted to double the overall interleaving period.

Comparing Maps 4 and 6, it can be seen that there is very little difference in the coverage obtained at the two bandwidths. This result was somewhat surprising. Close examination does show small differences between the results, particularly in dense and urban areas; however, these differences are not too great and could be considered to be within the range of day-to-day variation in results.

Comparing Maps 6 and 7, the improvement obtained by doubling the interleaving time can be seen. The improvement was particularly marked in the built-up areas such as the centre of Croydon. This result indicates that time diversity (in the form of interleaving) can be used to improve the coverage — providing the vehicle keeps moving. However, the effect can be seen to be different. When the COFDM bandwidth was reduced from 3.5 MHz to 1.75 MHz the proportion of central Croydon which was unserved was increased (particularly to the south and east). When the interleaving period was increased, much of the unserved area around central Croydon became marginal. The area affected remained more or less the same.

The benefit which can be achieved from interleaving depends on the speed of the mobile receiver. Further work would be required to quantify the benefit more accurately and, as a DAB service must also serve stationary receivers, it may not be very important.

8. ANALYSIS OF LOCATION VARIATIONS

8.1 Purpose of the measurements

Section 3.2 suggested that location variation is a particularly important parameter in the planning of a digital service such as DAB. A second phase of the work was, therefore, devoted to measurements of location variation for DAB signals. Since Eureka 147 has decided on a 1.5 MHz bandwidth for DAB signals, this work concentrated on measurements logged at approximately the narrower bandwidths.

8.2 Experimental procedure

The logging system was set to record field strength as the vehicle was driven round a number of half kilometre grid squares. The field strength data for each 500 m by 500 m square was processed to find the median and standard deviation. Only areas in which there were a statistically significant number of measurements were included. The areas surveyed included rural, suburban, urban and dense urban terrain. This was done for both 1.75 and 3.5 MHz bandwidth COFDM signals.

8.3 Analysis of received signal strength

A sample of the results obtained are shown in Table 2 *(overleaf)* for 1.75 MHz bandwidth, and Table 3 for 3.5 MHz bandwidth. The locations of the areas selected are shown in Map 8.

The standard deviations vary considerably between different locations, even for the same terrain category. Squares 15 and 16, for example, are both suburban locations yet they have vastly different standard deviations, particularly for 3.5 MHz bandwidth; these differences are discussed later.

Table 2
Analysed results for selected 500 m by 500 m boxes: Band III, 1.75 MHz bandwidth.

Terrain type	Square number	Standard deviation (dB)	Number of readings
Dense urban	1	4.5	178
Dense urban	2	6.0	147
Dense urban	3	5.3	194
Dense urban	4	7.0	146
Dense urban	5	4.8	121
Urban	6	3.5	219
Urban	7	5.8	139
Urban	8	8.0	93
Urban	9	4.5	112
Urban	10	5.0	182
Urban	11	5.0	178
Suburban	12	4.5	105
Suburban	13	7.0	160
Suburban	14	8.0	117
Suburban	15	6.0	220
Suburban	16	2.0	74
Suburban	17	5.0	140
Rural	18	3.0	72
Rural	19	5.0	47

Table 3
Analysed results for selected 500 m by 500 m boxes: Band III, 3.5 MHz bandwidth.

Terrain type	Square number	Standard deviation (dB)	Number of readings
Dense urban	1	5.5	85
Dense urban	2	7.0	109
Dense urban	3	3.5	174
Dense urban	4	7.5	111
Dense urban	5	4.5	107
Urban	6	5.5	144
Urban	7	5.0	105
Urban	8	4.5	117
Urban	9	5.5	189
Urban	10	5.0	101
Urban	11	4.5	207
Suburban	12	6.0	76
Suburban	13	6.5	168
Suburban	14	7.25	139
Suburban	15	7.0	187
Suburban	16	1.0	89
Suburban	17	4.3	47
Rural	18	2.0	100
Rural	19	4.5	126

Generally, the trends are similar for both bandwidths. That is, a square that exhibits a high deviation for 1.75 MHz also does so at 3.5 MHz. This increases confidence in the readings and suggests that they genuinely are a characteristic of the location.

It is sometimes possible to suggest reasons why some squares exhibit much higher field strength variations than others. Squares 2 and 4, for example, are situated in the central part of Croydon with its many high-rise buildings. In addition, 4 contains the Croydon underpass where considerable attenuation compared to ground level would be expected.

A possible reason for the high deviations in squares 14 and 15 is the relief of the land. This square contains a housing estate consisting of seven parallel curved roads. The western end of these roads lies on a slope facing the transmitter, whereas the other end lies in a slight dip. Previous survey work has shown that a low BER can generally be obtained at the west end of the roads, but in the dip at the other end reception often fails. Since the test route involved crossing back and forth along these roads, it might be expected that a high standard deviation would result.

Square 14 is partially obscured by a hill. Previous survey work shows that the shielding of the hill is less towards the western end. Again, therefore, the variations in field strength are probably explained by variations in the shielding.

Square 16 shows an unusually low standard deviation. Although much of the square has a direct line of sight to the transmitter, it contains a ridge of higher land. Most of the roads that were actually surveyed were in the shadow of this ridge, and produced a consistently low field strength. If roads on the other side of the ridge had been included, the results may well have shown a larger variation, i.e. the area was under sampled. This shows the effect of the choice of roads explored within the square. Ideally, all of them should be included.

Square 8 exhibits a large difference between the two bandwidths. This is probably because extra roads were included in the 1.75 MHz bandwidth survey. Variations encountered in this road may be responsible for the higher standard deviation. This illustrates the need to use the same roads in surveys if they are to be compared.

To allow comparison of the effect of changing the signal bandwidth, the data from a large number of the areas surveyed was analysed to produce overall values of standard deviations for each terrain type and both bandwidths. Table 4 shows the average standard deviation of signal variation for each terrain type. In the calculation, the contributions from each area were

Table 4
Variations in signal level for different DAB bandwidths and terrain types.

Terrain type	1.75 MHz bandwidth		3.5 MHz bandwidth	
	Standard deviation (db)	50% - 90% correction factor (dB)	Standard deviation (dB)	50% - 90% correction factor (dB)
Dense urban	5.5	12.9	5.6	13.1
Urban	5.2	12.0	5.0	11.7
Suburban	6.0	13.9	6.2	14.5
Overall mean	5.6	13.0	5.6	13.0

Table 5
Weighted average of standard deviation for the 1.75 MHz measurements over all the measured areas.

Terrain type	Number of 500 m by 500 m areas	Total number of measurements	Standard deviation of signal variation (dB)	50% - 90% correction factor (dB)
Dense urban	5	786	6.3	14.7
Urban	61	6262	5.5	12.8
Suburban	246	20496	5.8	13.5
Rural	26	1804	5.0	11.7
Overall	338	29348	5.65	13.2

weighted by the number of measurements in the sample in that area. These results show no indication that terrain type plays a significant rôle in determining the standard deviation. If there were an effect, the deviation would be expected to be highest for dense urban, and lowest for suburban. In fact, suburban areas give the slightly higher value. This is probably due to the fact that the available suburban areas were rather less flat than the other areas — the shape of the land has an effect more significant than the environment type.

Similarly, there is little change between the two values of bandwidth. Previous qualitative work supports this finding[7].

Once the system bandwidth had been fixed at 1.5 MHz, the complete set of data measured at 1.75 MHz bandwidth was taken and analysed. Table 5 shows the resulting terrain variations, which are very similar to those given in Table 4. The overall, average standard deviation of signal variation is essentially unchanged. The corresponding 50 - 99% correction factor, assuming the signal strength distribution is approximately log-normal, is found to be 13 dB.

9. DISCUSSION

Consideration of these results shows that the most dramatic improvements result from reducing the transmit frequency. The biggest degradations resulting from reducing the occupied bandwidth occur in cluttered areas. The changes are least significant when obstructions are caused by terrain features such as large hills.

The results show that the degradation introduced as a result of halving the COFDM bandwidth is more than offset by the improvement resulting from a reduction in the transmitted frequency. Extrapolating this result means that it will be important to investigate the performance of the system operating in Band II, as well as considering its performance with a 1.5 MHz COFDM bandwidth.

These results also show that in any area which is nominally 'served' there are always sections of road which are 'unserved'. This means that, in any operational system, a service criterion corresponding to a certain percentage of locations will need to be agreed. The percentage can never be 100%. Consideration should be given to what an acceptable percentage might be. Currently, discussions within the EBU indicate that a percentage coverage of around 99% might be acceptable.

The Band III results show that a large number of transmitters will be required to ensure the required service across the country. For example, relays would

be needed in the Kenley, Coulsdon, Selsdon areas, etc.; as these undulations in the terrain would probably not be filled satisfactorily, even if the transmitted ERP was increased by 10 dB or 20 dB. However, the use of an SFN approach with overlapping service areas should improve coverage as, not only will it make good the deficiencies, but also it will improve the percentage of locations served in the more marginal areas. This means that the planned single frequency network (SFN) experiment in this area will be an important investigation.

Observations in the measuring vehicle indicated that all the COFDM system failures occurred due to low field strength rather than long-delay multipath or interference from other Band III or Band IV signals. It will be important, as part of the next stage in this work, to measure and log the field strengths in these different areas.

Field strength logging experiments to date show that the required 50 - 99% correction factor for DAB is around 13 dB. This is considerably less than would be required for a conventional FM service and demonstrates the advantages of using a relatively wideband system for achieving uniform coverage to mobile receivers.

The measured values of DAB field strength location variation have been incorporated into the BBC computer prediction method, in order to improve the accuracy of the predictions[8, 9]. The measured results can also be used to examine and improve the accuracy of the computer predictions of median field strength.

This work, considering the location variation of the DAB signal for mobile measurement, can be combined with measurements which have already been reported for building penetration loss at Band III. Ref. 10 concludes that the building penetration loss to the ground floor of a brick-built building is, on average, 8 dB for conventional brick-built houses. As the standard deviation of the location variations from mobile measurements is 5.5 dB, this means that if 99% of locations are served to mobile receivers, then (on average) 80% of ground floor locations in the same area will be served. This is an important result, as it provides the first indication as to whether coverage criteria for mobile or portable receivers will be most critical. However, it should be noted that coverage criteria for portable reception are still being developed. They are particularly difficult to establish because of the problems of making measurements in a large number of houses and quantifying the effect of different house constructions on the building penetration loss.

10. CONCLUSIONS

A set of experiments has been performed to investigate the effect on the coverage area of reducing the COFDM bandwidth and changing the transmit frequency. The results show that the effect of halving the COFDM bandwidth from 7 MHz to 3.5 MHz was a small but significant reduction in the service area. This degradation was more than made up by reducing the transmit frequency from 531 MHz to 211 MHz. The effect of a further reduction in the COFDM bandwidth from 3.5 MHz to 1.75 MHz was found to be small.

It is concluded, that the choice, by the Eureka 147 Project, of a bandwidth for the DAB signal of approximately 1.5 MHz is suitable. This is because it is still sufficiently wideband to provide a significant benefit in reducing the location variation of the total received signal power, whilst being narrow enough to enable suitable channelisation within the existing frequency bands to be achieved.

It is also concluded, that a frequency allocation below Band IV is necessary to provide uniform coverage from terrestrial DAB transmitters. Above this frequency, the effects of clutter and terrain undulations increase the problems of providing uniform coverage to mobile and portable receivers.

The logged results provide quantitative information about the location variations. A value for the correction factor for 50% to 99% locations of 13 dB has been found. This should be proposed for use in national planning and international co-ordination of DAB networks.

11. RECOMMENDATIONS FOR FURTHER WORK

Further experiments are recommended to investigate the distribution of field strengths and the values of location variation at lower frequencies. In particular, the effect of transmitting the signal in Bands I and II should be considered.

In addition, a programme of work is recommended to investigate the effect on coverage of a single-frequency network of co-channel transmitters. This should seek to quantify the expected benefit in marginal areas from the simultaneous reception of signals from more than one transmitter.

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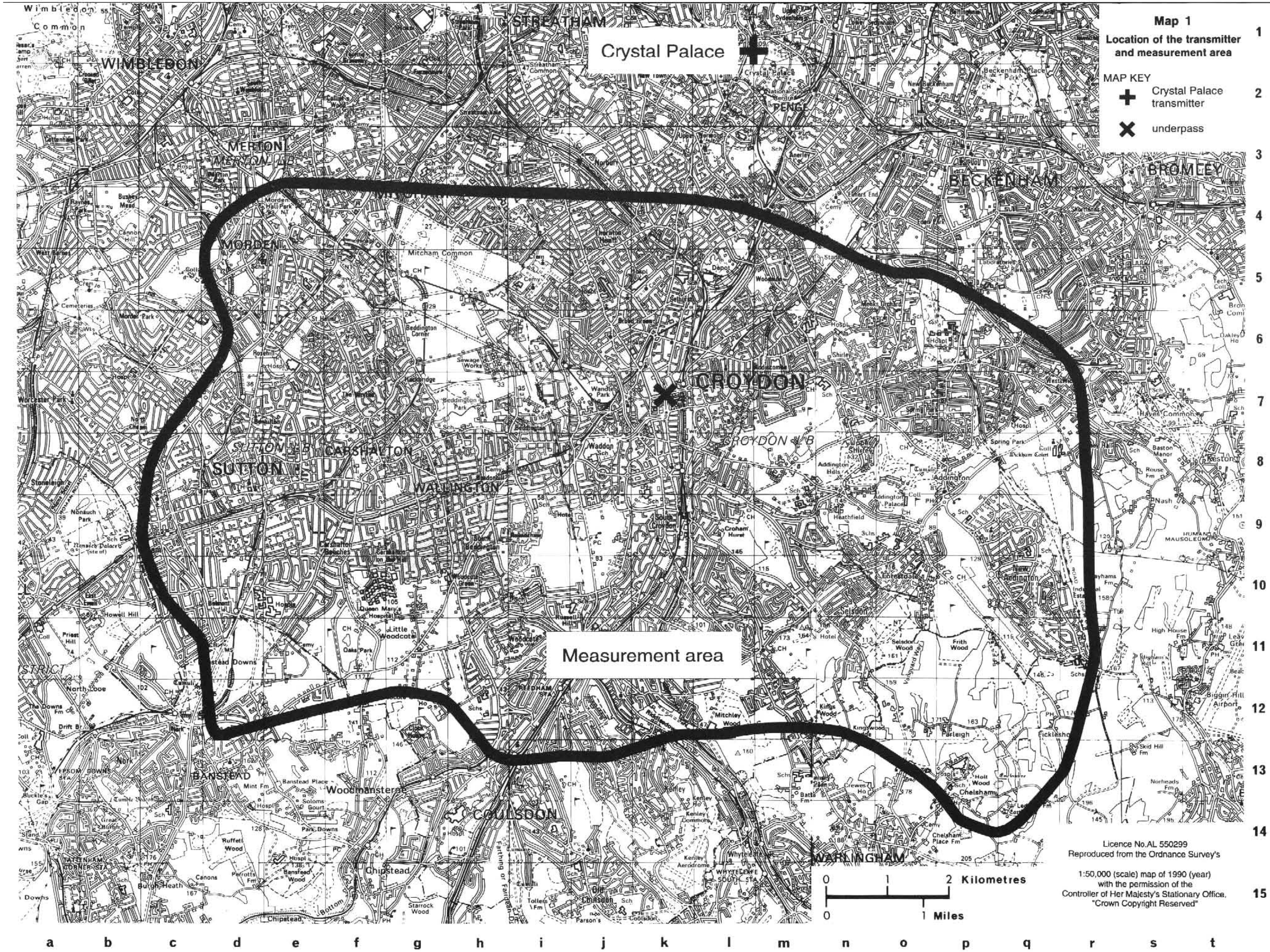
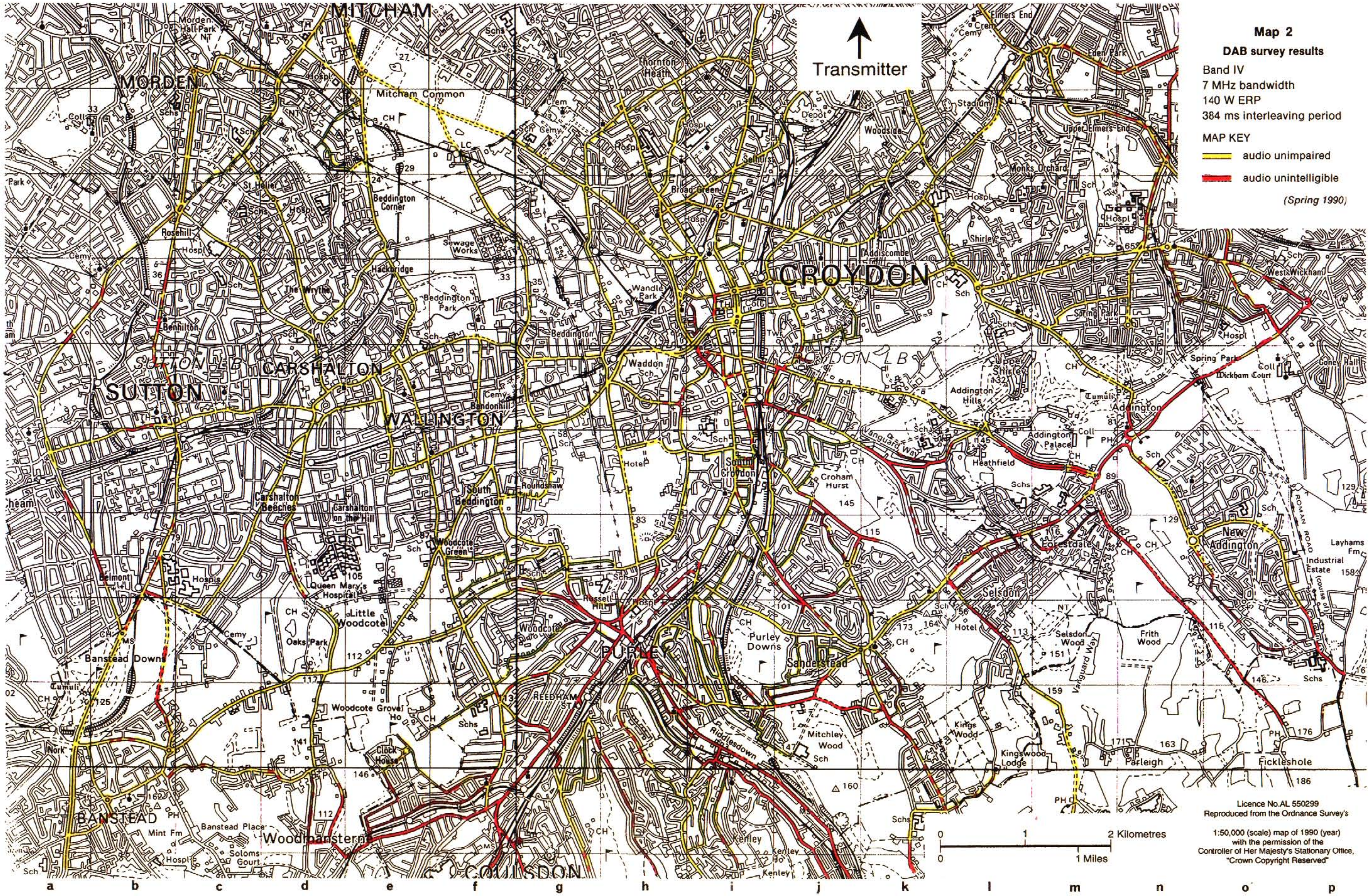

Map 1
Location of the transmitter and measurement area
MAP KEY
Crystal Palace transmitter
underpass
Crystal Palace
Measurement area
STREATHAM
WIMBLEDON
MERTON
MORDEN
BECKENHAM
BROMLEY
CROYDON
SUTTON
CARSHALTON
WALLINGTON
BANSTEAD
COULSDON
WARLINGHAM
Woodmansterne
Chipstead
PENGE
0 1 2 Kilometres
0 1 Miles
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
a b c d e f g h i j k l m n o p q r s t


Map 2
DAB survey results
Band IV
7 MHz bandwidth
140 W ERP
384 ms interleaving period
MAP KEY
audio unimpaired
audio unintelligible
(Spring 1990)
Transmitter
MITCHAM
MORDEN
SUTTON
CARSHALTON
WALLINGTON
CROYDON
PURLEY
COULSDON
BANSTEAD
Woodmansterne
New Addington
Selsdon
Sanderstead
0 1 2 Kilometres
0 1 Miles
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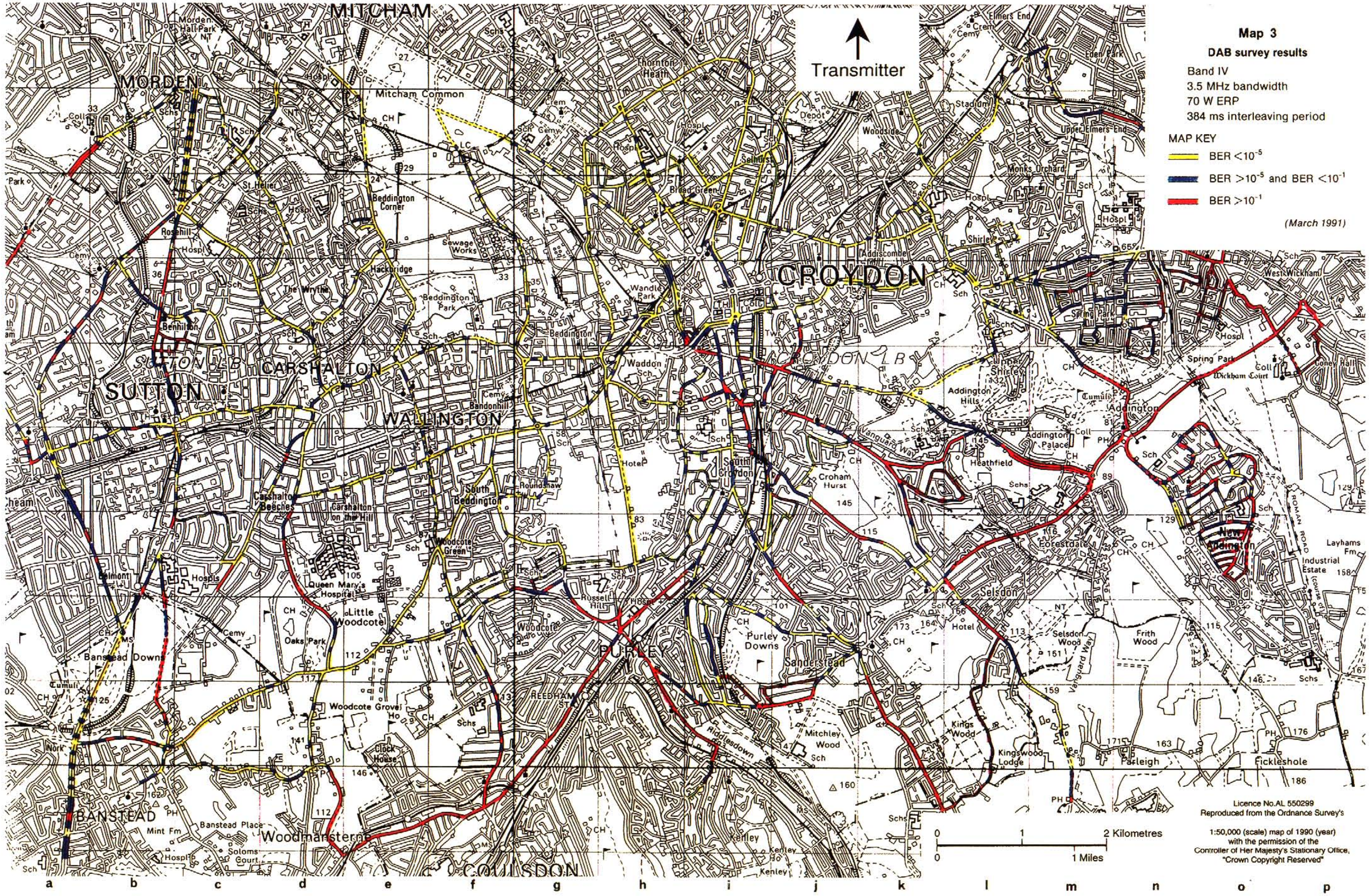
a b c d e f g h i j k l m n o p


Map 3
DAB survey results
Band IV
3.5 MHz bandwidth
70 W ERP
384 ms interleaving period
MAP KEY
BER <10^-5
BER >10^-5 and BER <10^-1
BER >10^-1
(March 1991)
Transmitter
MITCHAM
MORDEN
SUTTON
CARSHALTON
WALLINGTON
CROYDON
PURLEY
BANSTEAD
COULSDON
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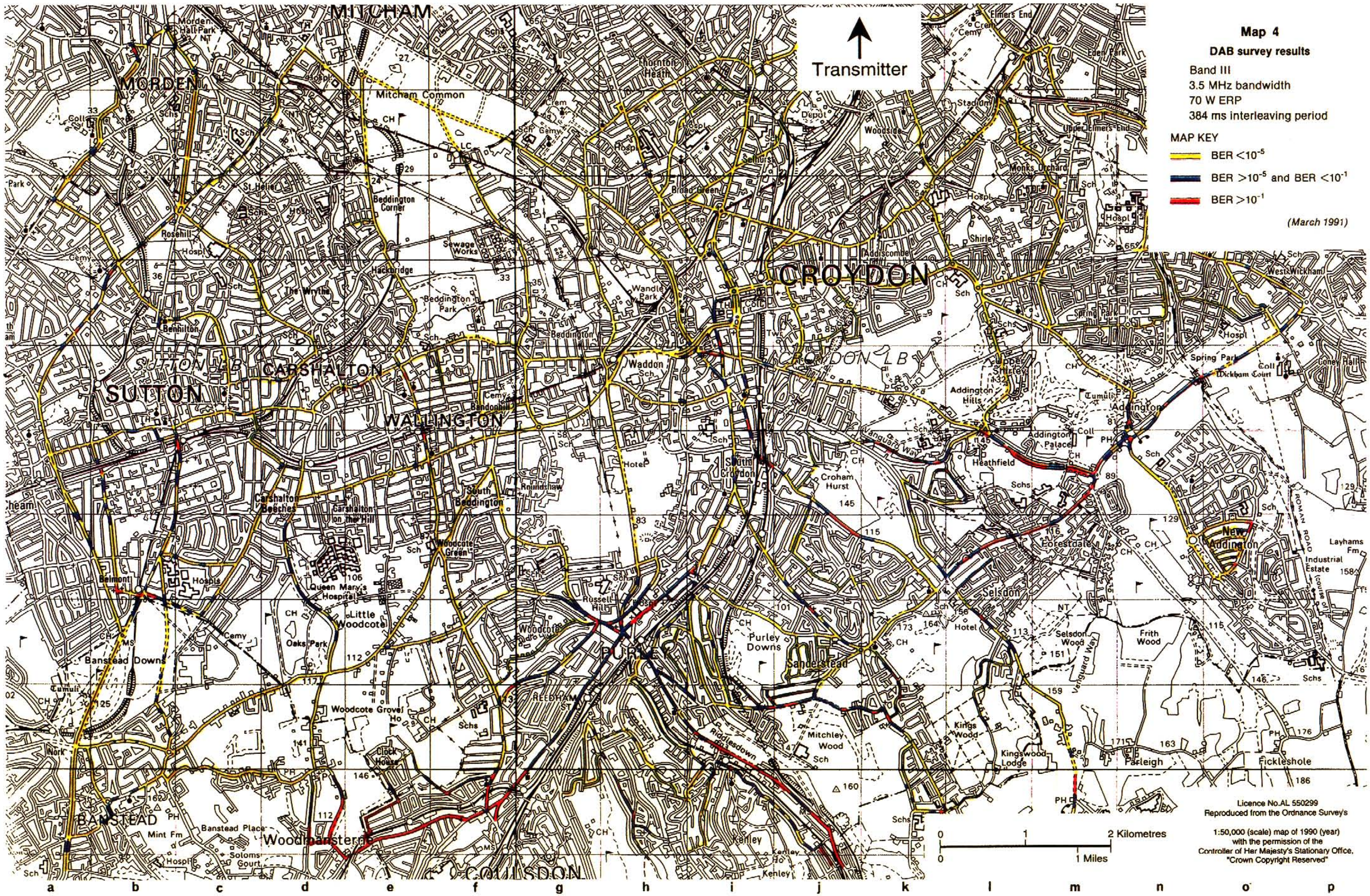
0 1 2 Kilometres
0 1 Miles
a b c d e f g h i j k l m n o p


Map 4
DAB survey results
Band III
3.5 MHz bandwidth
70 W ERP
384 ms interleaving period
MAP KEY
BER <10^-5
BER >10^-5 and BER <10^-1
BER >10^-1
(March 1991)
Transmitter
MITCHAM
MORDEN
CROYDON
SUTTON
CARSHALTON
WALLINGTON
PURLEY
BANSTEAD
COULSDON
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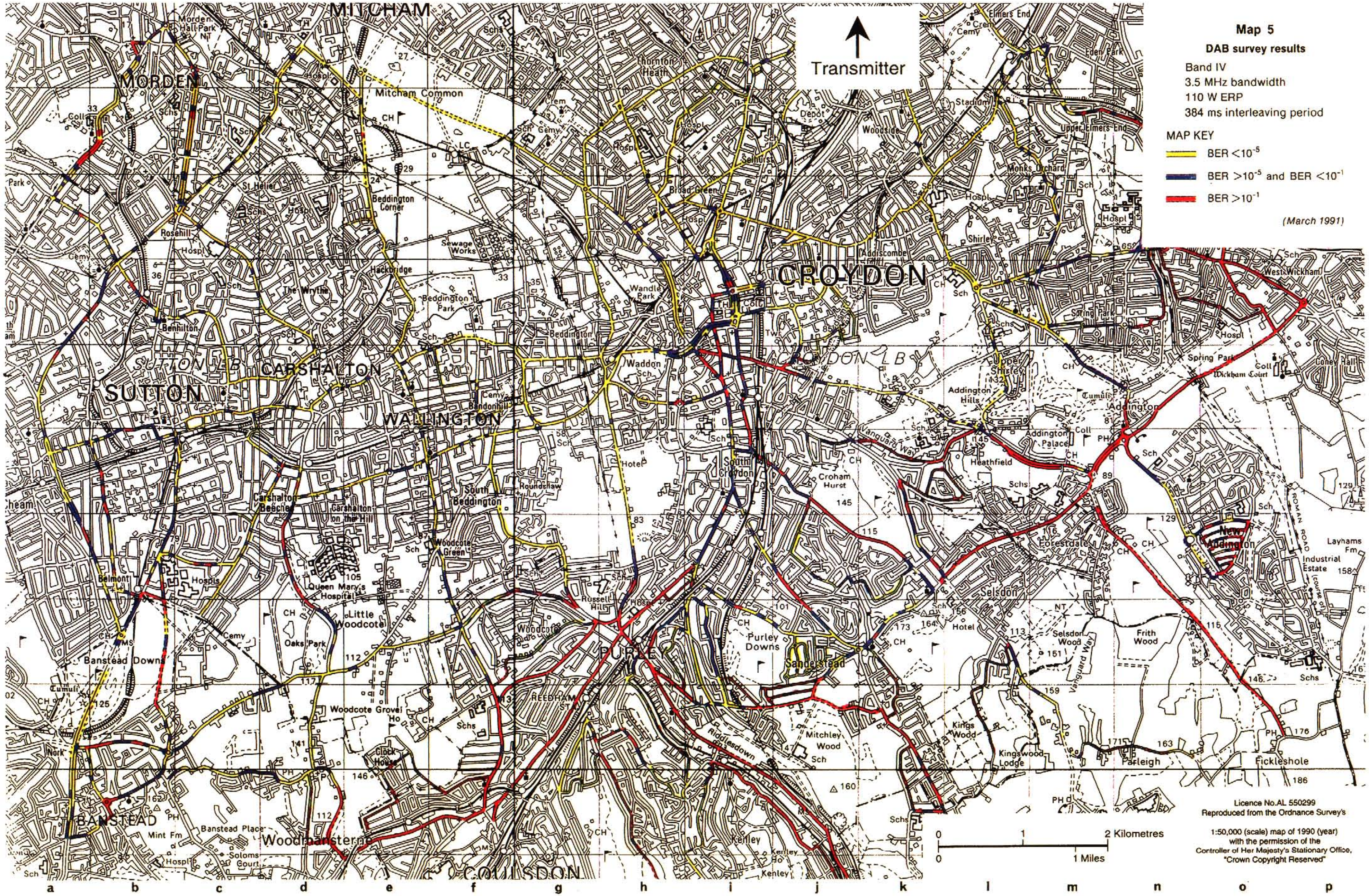
0 1 2 Kilometres
0 1 Miles
a b c d e f g h i j k l m n o p


Map 5
DAB survey results
Band IV
3.5 MHz bandwidth
110 W ERP
384 ms interleaving period
MAP KEY
BER <10^-5
BER >10^-5 and BER <10^-1
BER >10^-1
(March 1991)
Transmitter
MITCHAM
MORDEN
SUTTON
CARSHALTON
WALLINGTON
CROYDON
PURLEY
BANSTEAD
COULSDON
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0 1 Miles
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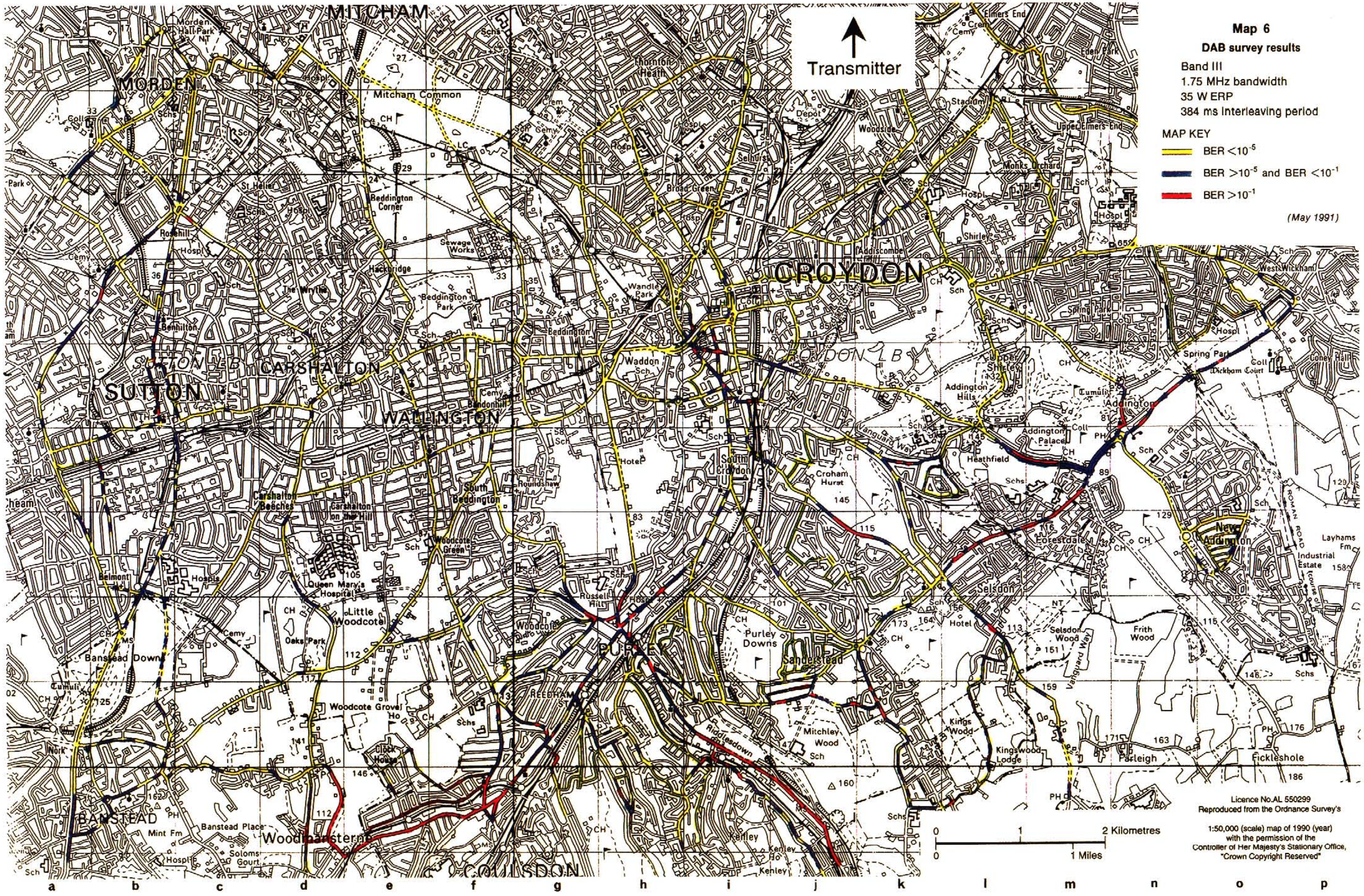
Map 6
DAB survey results
Band III
1.75 MHz bandwidth
35 W ERP
384 ms interleaving period
MAP KEY
BER <10^-5
BER >10^-5 and BER <10^-1
BER >10^-1
(May 1991)
Transmitter
MITCHAM
MORDEN
CROYDON
SUTTON
CARSHALTON
WALLINGTON
PURLEY
COULSDON
BANSTEAD
0 1 2 Kilometres
0 1 Miles
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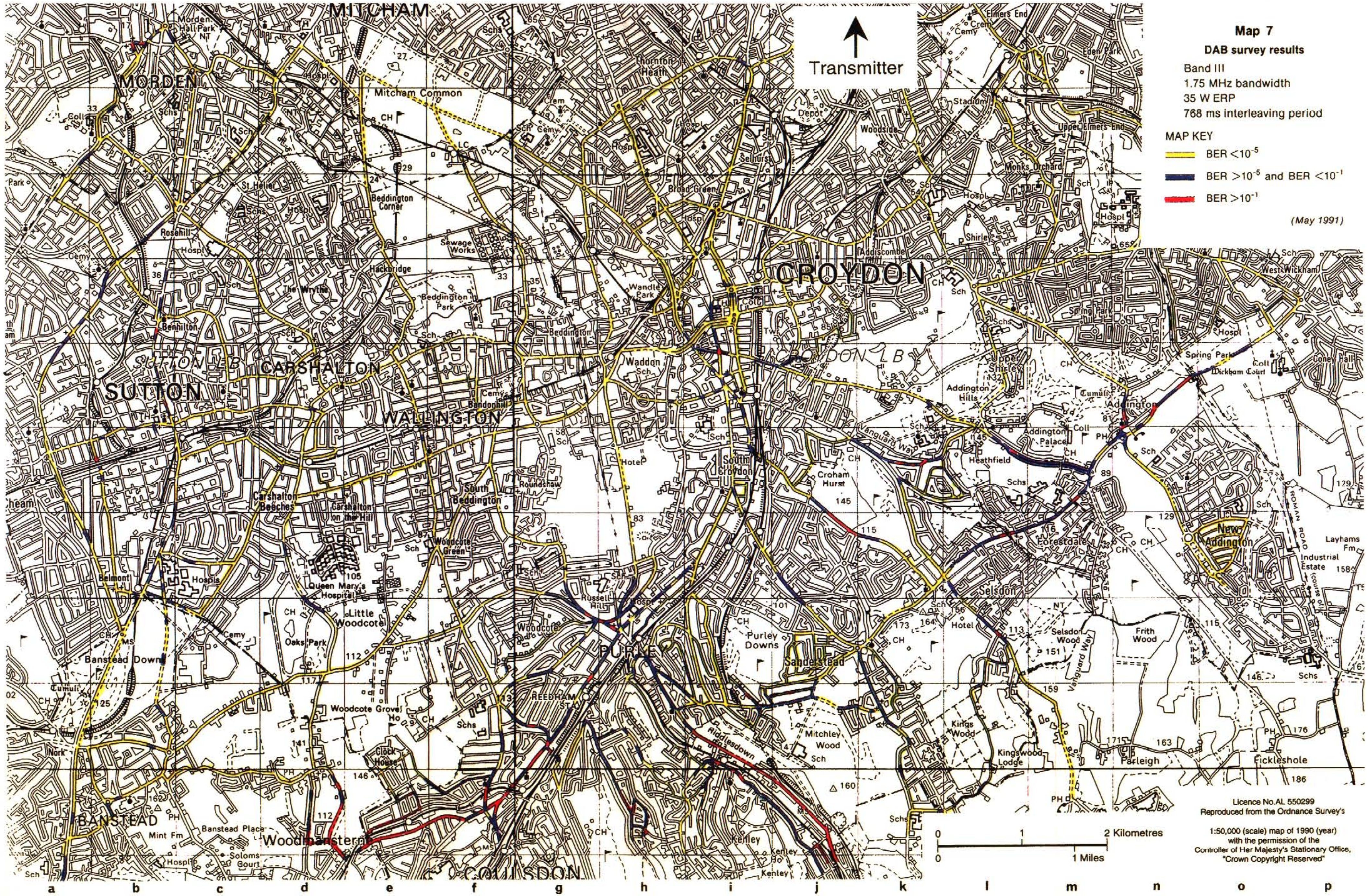
Map 7
DAB survey results
Band III
1.75 MHz bandwidth
35 W ERP
768 ms interleaving period
MAP KEY
BER <10^-5
BER >10^-5 and BER <10^-1
BER >10^-1
(May 1991)
Transmitter
MITCHAM
MORDEN
CROYDON
SUTTON
CARSHALTON
WALLINGTON
PURLEY
COULSDON
BANSTEAD
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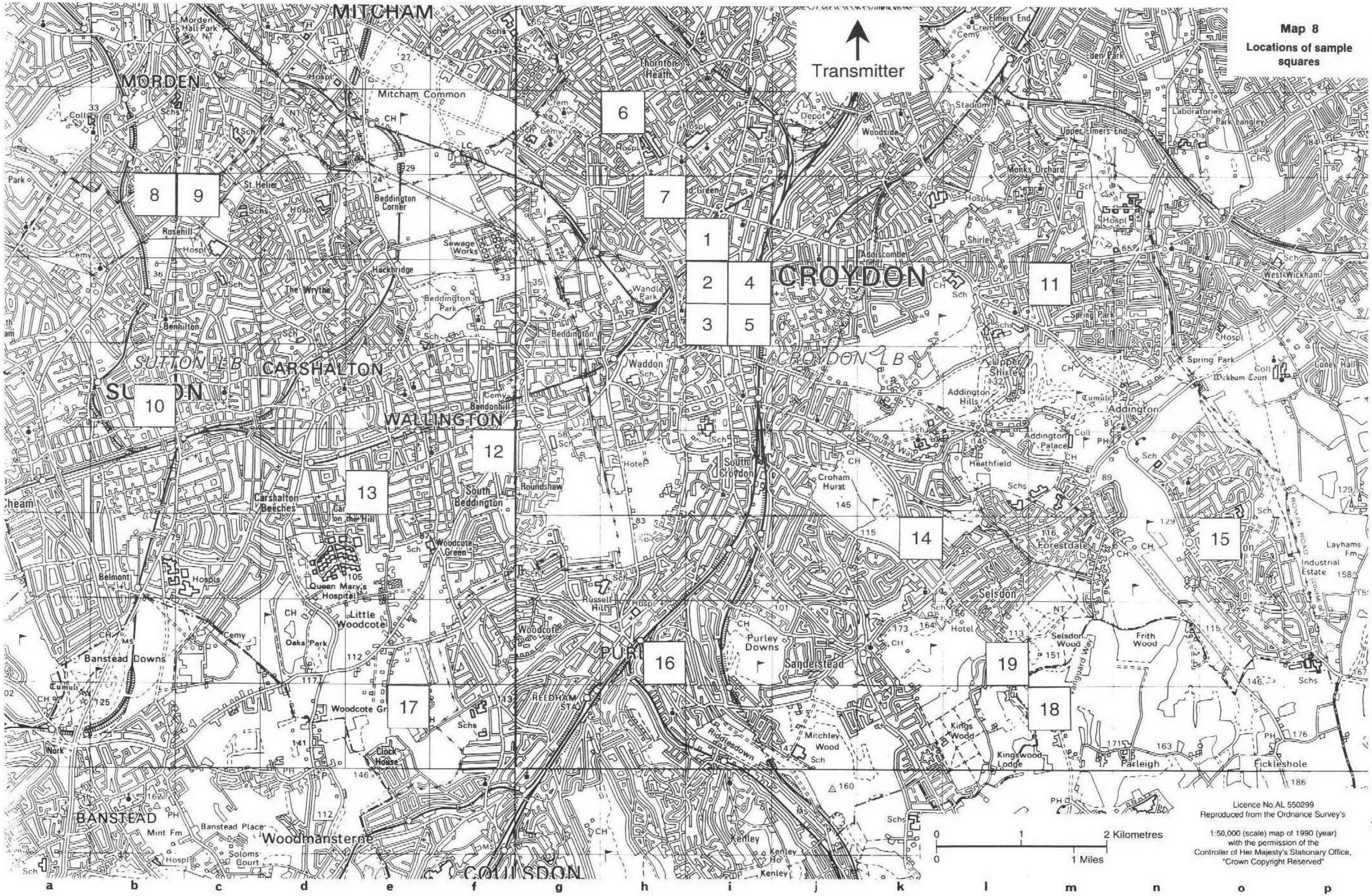
0 1 2 Kilometres
0 1 Miles
a b c d e f g h i j k l m n o p



Map 8 Locations of sample squares

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